Differential-Mode Branch-Line Directional Couplers

J. Sorocki, I. Piekarz, K. Staszek, P. Kaminski, K. Wincza, and S. Gruszczynski

***Abstract*—In this letter, a novel approach to the design of a commonly known branch line directional couplers is presented for operation in a differential mode. The couplers are analyzed in a two-mode structure and realized in a symmetric two-conductor-over-ground transmission line technique. Moreover, the investigation on the possible miniaturization of such circuits is presented. The results of theoretical analysis are verified by the measurement of the fabricated circuits.**

***Index Terms*—Balanced-mode components, directional couplers, branch-line couplers, miniaturized couplers.**

I. Introduction

In contemporary electronics it is common practice to interconnect the devices using balanced lines, since they offer superior properties in terms of interference rejection. Such balanced interconnections are applied in standard circuits designed on a laminate, where the interconnections between different integrated circuits are made, as well as at the monolithic integrated-circuit scale level, where signals in monolithic technology are distributed using balanced lines. In literature one can find many reports on the utilization of balanced-line interconnections in various types of circuits such as mixers [1], amplifiers [2], frequency doublers [3] or filters [4]. Also, recently mixed-mode scattering parameters have been introduced as a useful tool for the differential and common-mode circuit description [5]. In practice, a common technique is to employ balanced-to-imbalanced transformers when some signal operations, such as power split, filtering, power combining, etc., are needed. Such an approach, however, results in a circuit complexity and makes the circuits more prone to the interferences related to the utilization of a common mode.

In this paper, a novel concept of the realization of a well-known branch-line directional coupler is presented. The coupler is designed in a way that exhibits its properties for a differential mode, and therefore, is suitable for utilization when different circuits having differential inputs/outputs are interconnected. On the other hand, such a circuit can be very useful for direct distinction and measurements of differential-mode reflected and incident waves, and therefore, can be used for measurements of differential-mode *S* parameters. In this paper two branch-line directional couplers are investigated, i.e. a directional coupler being a direct conversion between single-ended and differential circuit, and its miniaturized version, where a transmission line sections are electrically shortened by a capacitive loading [6]. The results of theoretical investigation have been supported by the measurement results of the designed and manufactured components for final verification of the circuits properties. The directional couplers have been designed in a two-conductor-over-ground transmission-line technique. In order to allow for measurement of the designed coupler, simple balun circuits have been applied at each of the couplers' input ports.

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II. Differential-Mode Branch-Line Directional Coupler

Fig. 1 illustrates a schematic diagram of the directional coupler designed for operation in a differential mode. Since the aim is to incorporate the circuit in a system having, in general, common ground reference, the circuit needs to be analyzed using coupled-line section models.

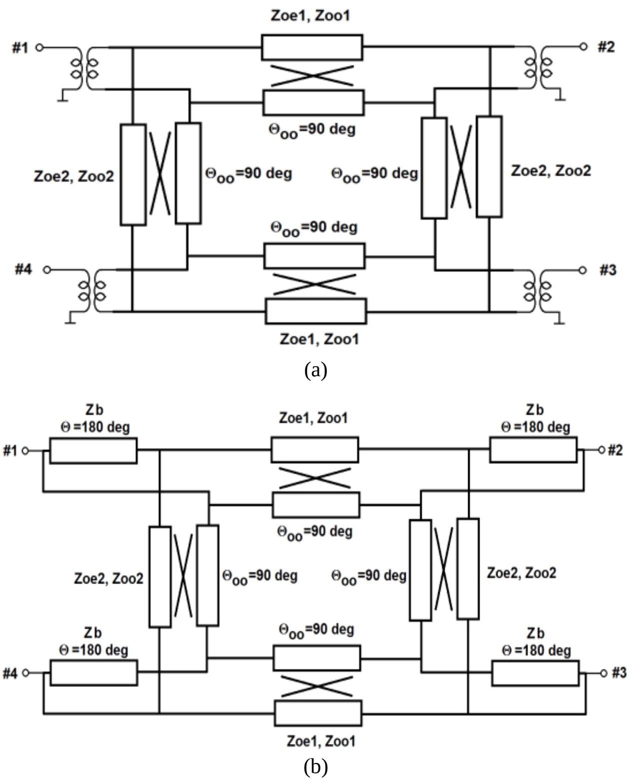

Fig. 1. Schematic diagram of the branch-line directional coupler for differential-mode operation. The circuit with ideal baluns applied at each port (a) and the corresponding coupler with baluns composed of a half-wavelength transmission-line section (b).

Such an analysis takes into consideration both modes that can propagate in the structure, i.e. common mode and a differential one. In order to investigate the differential properties of the circuit, ideal transformers have been applied at each of the coupler's ports. For such excitation the circuit

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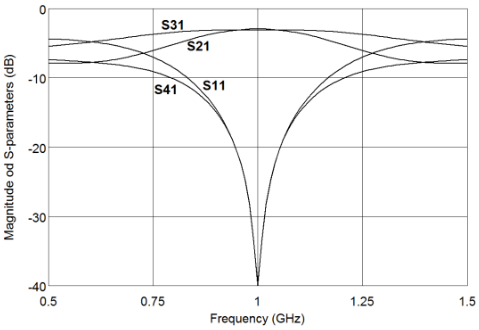
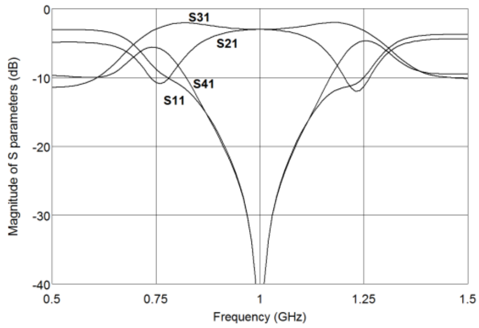
preserves the properties of an equal-power-split directional coupler when the following conditions hold:



(a)



(b)

Fig. 2. Scattering parameters of the differential-mode branch-line directional coupler excited with ideal balus (a), baluns realized with half-wave-long transmission line (b). Results of circuit analysis.

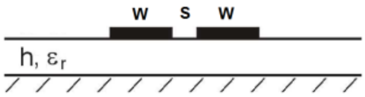
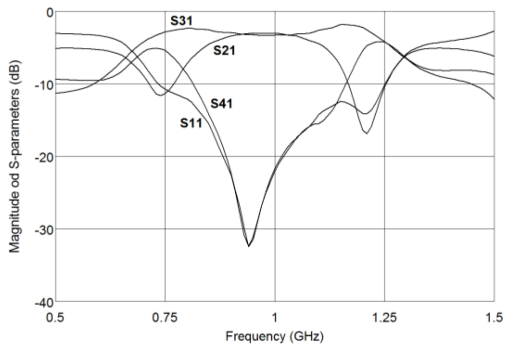
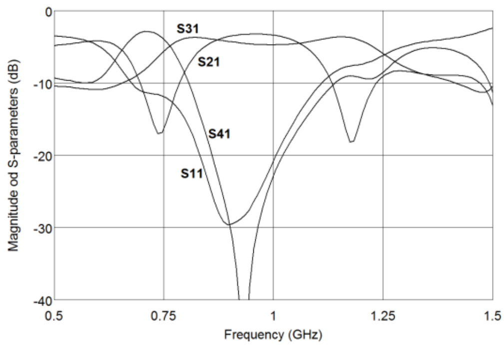


Fig. 3. Cross-section of the dielectric structure used for the design of the differential-mode branch-line directional coupler.



(a)



(b)

Fig. 4. Scattering parameters of the differential-mode branch-line directional coupler designed in the dielectric structure shown in Fig. 3. Results of electromagnetic calculations (a) and the measured results of the manufactured coupler (b).

$$Z_{OO1} = Z_{Tdiff} / (2\sqrt{2}),\ \ Z_{OO2} = Z_{Tdiff} / 2 \qquad (1)$$

where Z_{oo} is the characteristic impedance of the coupled-line section differential mode and Z_{Tdiff} is the terminating impedance for the differential mode. The calculated scattering parameters of the ideal circuit are presented in Fig. 1(a). One can notice that under conditions (1) the frequency response of the coupler resembles the frequency response of a single-ended directional coupler. In order to make a physical realization and further measurement verification possible, the ideal transformers have been replaced with baluns constituted by half-wave-long transmission-line sections as shown schematically in Fig. 1(b). The applied balun circuits constitute ideal baluns at the center frequency regardless of the choice of their characteristic impedance Z_b. The *S* parameters of the circuit presented in Fig. 1(b) are plotted in Fig. 2(b). One can notice that the in-band response of the circuit is intact, while out-of-band response is slightly modified. The considered circuit has been designed in a dielectric structure shown in Fig. 3 for which the dielectric thickness equals h = 1.54 mm and the relative permittivity equals ε_r = 3.38. The geometry presented in Fig. 3 is a classic microstrip coupled-line geometry, in which for the purpose of our investigation only the differential mode needs to be excited. Since the applied balanced circuits transform the impedance with the ratio Z_{Tdiff} / Z_{in} = 4 the resulting differential-mode characteristic impedances of the directional coupler equal Z_{oo1} = 70.71 Ω and Z_{oo2} = 100 Ω. The resulting strip widths and gaps are as follows: w = 0.15 mm, s = 0.3 mm for the section having impedance Z_{oo2} = 100 Ω, and w = 0.35 mm, s = 0.2 mm for the section having impedance Z_{oo1} = 70.71 Ω. The results of both electromagnetic calculations and measurements of the designed structure are presented in Fig. 4. One can notice a very good agreement between the theoretical and experimental results in terms of return losses as well as transmission responses. As it is seen from the schematic, the realization of the considered directional coupler in a proposed technique requires cross-connections of the conductors, which were realized as bonds between strips with a 0.25 mm dia. wire.

III. Miniaturized Differential-Mode Branch-Line Directional Coupler

Further, the possibility of miniaturization of the considered branch-line directional couplers has been investigated.

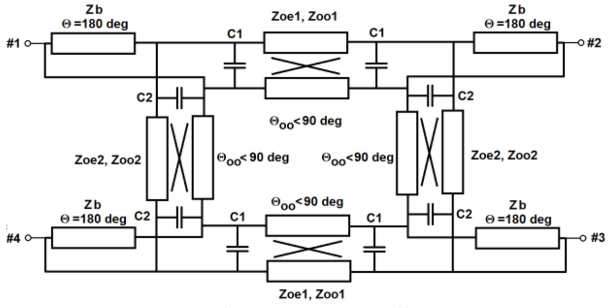
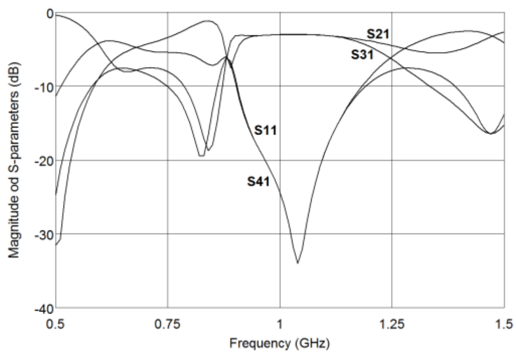
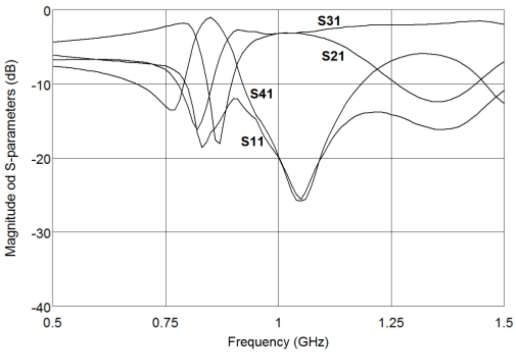


Fig. 5. Schematic diagram of the miniaturized differential-mode branch-line directional coupler with baluns composed of a half-wave-length transmission-line section.

In order to achieve size reduction, the transmission-line sections have been electrically shortened by capacitive loading following the method shown in [6]. The schematic diagram of the miniaturized coupler is presented in Fig. 5, while the obtained results are presented in Fig. 6. For the realization the following capacitance values have been chosen: C_1 = 0.5 pF and C_2 = 1 pF which results in the following parameters of the transmission-line sections: $Z_{oo1} = Z_{oo2} = 162\Omega$ (w = 0.1 mm, s = 0.8 mm), $\Theta_1 = 26°$ and $\Theta_2 = 40°$. One can see that the obtained theoretical as well as experimental characteristics of the miniaturized directional coupler correspond to the classic one, while the overall size of the coupler has been significantly decreased (by over 7.7 times in terms of the occupied area).



(a)



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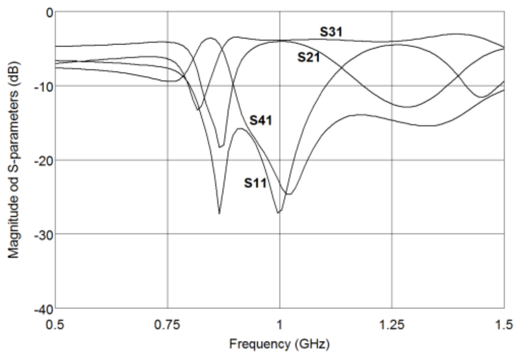

(c)

Fig. 6. Scattering parameters of the miniaturized differential-mode branch-line directional coupler. Results of circuit analysis (a), electromagnetic calculations (b) and measurements (c).

The required capacitances have been realized by application of commercially available SMD components (size 0402), while the required transmission-line cross-connections have been made with SMD 0 Ω chips (size 0603). A photograph of the manufactured circuits is shown in Fig. 7.

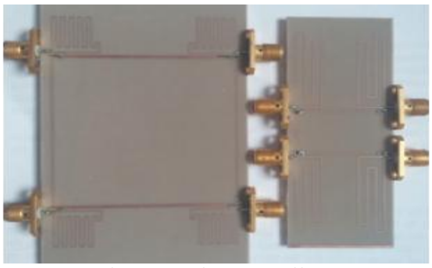

Fig. 7. A photograph of the manufactured differential-mode directional couplers. The meandered transmission-line sections at each of the ports constitute balun circuits for single ended measurements.

IV. Conclusion

In this paper, a novel approach to the design of the branch-line directional coupler has been shown. The designed couplers operate in a differential mode and are suitable for interconnection of circuits with balanced input/output ports. Moreover, successful miniaturization of such networks has been shown. The theoretically considered circuits have been designed, manufactured and measured. The measured results prove the possibility of differential-mode branch-line directional couplers' realization.

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